A Novel Approach to Sensor-less Daylight Harvesting in Commercial Office Buildings

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Abstract

The rise of energy costs is negatively impacting operating budgets for buildings. Energy efficient programs are being implemented during the design phase of buildings to maximise occupancy comfort and reduce energy consumption. The problem for investors is that the cost to install these energy efficient products have questionable investment returns.

Through theoretical and subsequent empirical analysis, this paper introduces a mathematical equation that replaces existing sensor controlled daylight harvesting control systems. This is achieved using an exponential distribution that takes a weather station lux reading to identify the natural light at any given point in a building. This equation makes it possible to calculate the dimming level required to achieve a designed lighting level that uses both natural and artificial light. This sensor-less daylight harvesting method will provide building owners with an alternative, less expensive, and more efficient daylight harvesting control system.

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1 Introduction

Daylight Harvesting (DH) in a commercial building considers the illumination effect of natural light to offset artificial lighting illuminance at a working plane or building gathering place (Yu and Su, 2015). The DH benefit to the owner is that the demand for power is reduced, thereby reducing light fitting power consumption costs and maintenance factors as the time in use of the light fittings is extended. Academic research suggests that the power demand of artificial lighting equates to "approximately one-third of electricity used in commercial buildings" (Soori and Vishwas, 2013). Understanding the actual power consumption of a light is needed to identify the return on investment (ROI) and to evaluate the effectiveness of a proposed lighting cost minimisation strategy. Observations of industry practice revealed that DH in both new construction projects and existing buildings is not regularly adopted. This is supported by research that suggests "lighting control is not popular", and that the unenthusiastic adoption of DH lighting control is due to the absence of local daylight data and lighting cost analysis (Li et al., 2009).

With the energy consumption of a lamp being "roughly proportional" to the output illuminance (Ticleanu, 2015). Li et al. (2009) identified predictive energy cost savings is possible by using a daylight factor (DF). This supports the evidence that dimming light fittings with sensors will decrease energy costs (Kacprzak and Tuleasca, 2013, Li et al., 2006). However, the perceived problem with implementing this theoretical finding lays in the functionality of lighting control systems that is limited to manual test and pre-set scenes, or installing lux sensors in the ceiling located at determined intervals around the perimeter of an office space. Whilst the benefit of dimming control in relation to energy efficiency has been thoroughly researched, linking this literature to investor ROI appears limited. A google search of DH identified numerous companies that promote the benefits of their products and the energy savings that is possible from DH, but don't provide any ROI data, highlighting the gap in industry and literature on DH processes and lighting control interfaces.

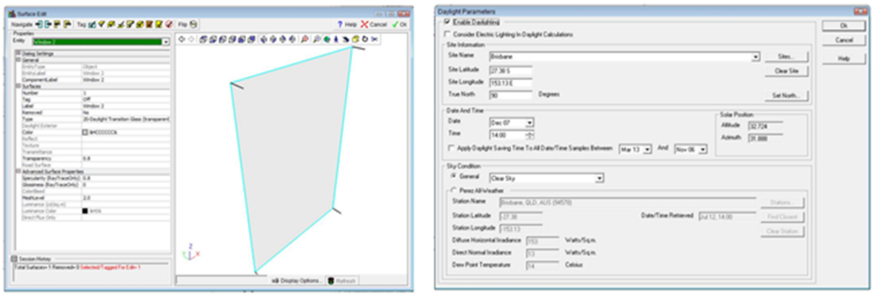
This novel approach differs from other sensor-less DH (SDH) studies that are limited to using photovoltaic (PV) generation (Yoo et al., 2014). The PV approach is not deemed an acceptable approach to dim lights in commercial buildings as the study didn't address regulatory lux level requirements, variables such as shadowing from neighbouring buildings, cost of implementation, and the effect that random clouding has on internal building light levels. This paper demonstrates that SDH is possible, and with future research it can be automated to provide Owners with a cost-effective DH solution.

2 Methodology

An addressable lighting control system, AGI or Dilux light modelling software, mathematical software, and a roof top weather station is required for a SDH system. Whilst lighting software is available for new buildings to model light levels, the final SDH solution doesn't require this software as it was cost prohibitive due to the time costs of re-designing lighting layouts in existing buildings that don't have computer aided drawings (CAD) files. The following section is included in this research as the AGI32 software provided the theoretical data.

2.1 Lux Modelling Software

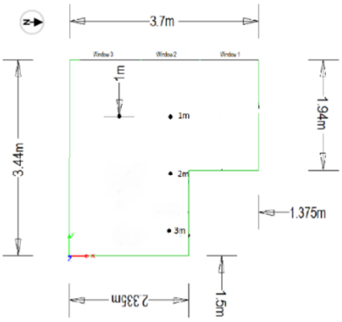
Current lighting design practices generally do not include external lighting sources other than artificial light sources modelled in the AGI32 software program. To verify the accuracy of internal light, a transition glass setting that combines natural light with artificial light in a building was used (Figure 1). Verifying the calibration process to achieve a "real life" lux plot calculation was not carried out as this process was proven possible by Kacprzak and Tuleasca (2013).



☑ Enable Daylighting
☐ Consider Electric Lighting In Daylight Calculations
Site Name: Brisbane
Site Latitude: 27.38 S
Site Longitude: 153.13 E
True North: 90 Degrees
Date: Dec 07
Time: 14:00
☐ Apply Daylight Saving Time To All Date/Time Samples Between Mar 13 And Nov 06
Solar Position Altitude: 32.724
Azimuth: 31.888
Sky Condition: ● General Clear Sky
○ Perez All Weather
Station Name: Brisbane, QLD, AUS (94578)
Station Latitude: -27.38
Station Longitude: 153.13
Date/Time Retrieved: Jul 12, 14:00
Diffuse Horizontal Irradiance: 153 Watts/Sq.m.
Direct Normal Irradiance: 13 Watts/Sq.m.
Dew Point Temperature: 14 Celsius

Figure 1 - Transition Glass and Sun Setting

The AGI32 software program (Figure 1) was used to identify the relationship between external light and internal light at three internal plot (x) locations (Figure 2). This provided a platform to verify existing literature, and subsequently led to the discovery of a scalar factor (SF) that is defined in section 2.3. In addition to this, the transition glass setting was used (Figure 3) to identify an exponential lighting distribution curve that has been recognised in literature as a fact (Singhvi et al., 2005).



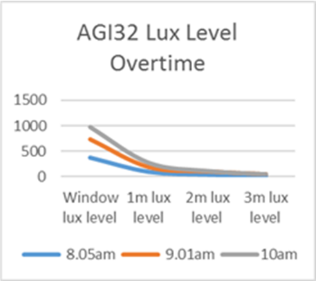


Figure 2– Room Layout

Figure 3 – AGI32 Lux Level in Room Exponential Shape Test

2.2 Modelling the Effects of Lighting Variables

To effectively maintain lighting levels to Australian/International Standards, SDH considered the following variables and the ease at how these variables can be calculated and incorporated in the design and commissioning phase of a SDH system.

External

1. Atmospheric variables that include; a) clear sky with direct sunlight, b) random cloud events, and c) overcast skies.
2. Positon of Sun during the four seasons, Winter, Autumn, Summer, and Spring.
3. Shadowing impact to the lux levels from block structures such as neighbouring buildings, trees, or bridges etc.

Internal

1. Window tinting and internal partitioning.
2. Interior partitions, Interior Design/Art Work, and alterations over time.
3. External light entering a room from different sides.
4. Blinds (Blinds in a building that does not have auto control will be set in the SDH to the translucency factor of the blind).

The **external variable** is managed by a weather station and onsite commissioning that adjusts the SF to the floor areas that are affected by shadowing structures. The **internal variables** are deemed to be constant, and therefore the SF accounts for these variables during the SDH commissioning phase. Lighting control systems have the capability of managing blinds, but that is a lighting control design parameter that will be addressed in future research.

2.3 Exponential function – One Side Light Entry Only

Experimental tests using both the AGI32 software and samples taken using the light meter demonstrated a correlation between the rise in the indoor and outdoor lux level. This ratio of internal illuminance to external illuminance is defined as 'Daylight factor' (DF) by the CIE (International Commission on illumination). The mathematical definition is as follows:

$$DF = \frac{internal\ illuminance}{external\ illuminance} * 100\% \qquad \text{(equation 1)}$$

The difficulty with using this DF equation to accurately predict the dimming threshold to control artificial light, is that the variables impacting external light penetrating the building façade remain unaccounted for. Furthermore, reflectance of internal room surfaces, the orientation and location of the room, the size of the room, and amount of direct and or indirect light are all variables that need to be calculated to accurately determine internal illuminance. Likewise, external illuminance depends on the time of day, the date, atmospheric conditions and weather patterns. CIE adopt the approach of minimising some of these variables by standardising the DF definition to overcast sky conditions (Bian and Ma, 2017). This research used the AGI32 software to provide internal lux levels for natural light using CIE overcast sky conditions (Lighting, 2016) . The simulation of a full day revealed that once the initial variable in the building structure is calculated (which was the size of the window and the layout of the room in the sample), the rise in internal and external lighting levels was linear. Therefore, the hypothesis is that irrespective of the weather condition, as long as the variables remain constant, a linear relationship between the amount of external illuminance, in proportion to the internal illuminance at a particular point will occur. This scalar value is dependent on the exponential function of the decaying luminance intensity, and is different (exponentially) at any given distance from the window.

$$SF = \frac{external\ Lux\ value}{internal\ Lux\ value} \text{ for a specified distance value from the window. (equation 2)}$$

Using equation 2, the external lux value can be determined by using an exponential function that considers the horizontal grid sample of internal lux values at incremental distances (x) from the window, and multiplying by SF. Similarly, the external lux value divided by SF will result in the internal value at each grid point. This linear relationship, of external light to internal light results in SF with the proportionality being dependant on 3 variables as described in International Commission on Illumination (CIE); sky component (SC), externally reflected component (ERC), and the internally reflected component (IRC) at each sample grid point.

Through the calculation of SF from actual grid point samples, light level variables can be accounted for, and SF can be adjusted during the "building tuning" phase to provide greater accuracy to light levels at the working plane (Kacprzak and Tuleasca, 2013). Table 1 shows the lux values recorded from the AGI32 room simulation and the distance plots from the window. Mathematically the function of the data set (Figure 6) can be represented in the "base-intercept" or in the "relative-rate-intercept" form as per equation 3

Table 1 - Lux levels from Office space experiment

Distance (*x*) from Window (Meters)	**Internal Lux Level (y)**	**External Lux level**
1	1345	15113
2	913	15113
3	650	15113

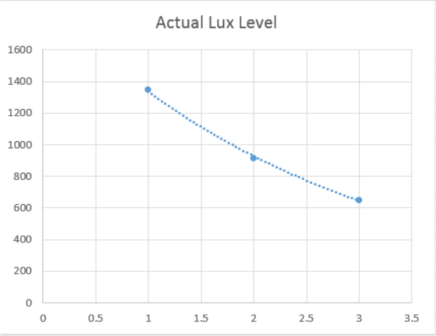


Figure 6 – Office room Lux levels

$y = P(0)a^x \ or \ \ y = P(0)e^{rx}$ (equation 3)

In equation 3, $a^x \ and \ e^{rx}$ are equal to the base of the exponential function. The number *r* is called the "relative rate" of the exponential function and determines the shape of the slope and rate of change of the graph. From equation 3 the following is determined:

$P(0)a^x = P(0)e^{rx} \quad the\ P(0)\ cancels\ and\ we\ are\ left\ with,$

$a^x = e^{rx} \ = \ e^{(r)x} \ therefore,$

$a = e^r \ and \ r = \ln(a)$ (equation 4)

$a = \left(\frac{y2}{y1}\right)^{\frac{1}{x2-x1}}$ (equation 5)

In equation 5, (x1,y1) and (x2,y2) are points on the graphed exponential function (Kacprzak and Tuleasca, 2013). For the purpose of SDH, the x-axis values represent the distance from the window, and y-axis values are the lux levels at the distance from the window (x). To obtain a function formula, a minimum of three sampled values is recommended. Equation 6 identifies the rate of change when applying equations 4 and 5 to a lux sample of 1 meter from the window = 1345lx, and 2 meters from the window = 913lx.

$$r = \left(\frac{\ln(y2)-\ln(y1)}{x2-x1}\right) \qquad \text{(equation 6)}$$

$$\mathrm{r} = \left(\frac{\ln(913)-\ln(1345)}{2-1}\right)$$

$$\mathrm{r} = -0.387413411$$

$y = P(0)e^{-0.387413411x}$ Modifying equation 3 to include the function.

To calculate P(0) (initial value of x from 1 to ∞) x=1 and y=1345.

$$1345 = P(0)e^{-0.387413411*1}$$

$$P(0) = 1345/(e^{-0.387413411})$$

$P(0) = 1934.76$ (y intercept of the function when $x \approx 0$)

With each variable isolated, equation 3 returns the internal lux level in an exponential expression.

$$y = 1934.76e^{-0.387413411x} \qquad \text{(equation 7)}$$

Equation 7 is derived from two coordinate points which can produce a higher error rate. Therefore, to improve the accuracy of P(0) and r, at least 3 coordinate point samples is recommended. Equation 7A demonstrates a better approximation of the internal lux value, by calculating P(0) and r at each sampled point of x by taking the average $\frac{1}{n}\sum_{i=1}^{n} P(0)i$ and $\frac{1}{n}\sum_{i=1}^{n} ri$, where n is the number of sampled lux values. Increasing the n samples will improve the accuracy, however considering the commercial application of SDH it is determined that 3 lux plot tests will satisfy compliance to lux level standards.

$$y = 1919.57e^{-0.363588465x} \qquad \text{(equation 7A)}$$

To verify the accuracy of the algorithm, the following calculates y (internal lux level) for each value of x (distance from window) to compare the original lux values.

Table 2 – Internal Lux Sample Compared to Exponential Lux Value

Distance (*x)* from Window (Meters)	**Internal Lux Level (y)**	**Internal Exponential Lux Level (y)**
1	1345	1334.44
2	913	927.68
3	650	644.9

To verify the external lux level (Elux) accuracy, equation 8 provides a sanity check that can be easily calculated during the commission phase of SDH implementation.

$SF = \frac{external\ Lux\ value}{internal\ Lux\ value} = \frac{15113}{1345} = 11.2364$ For x=1

$SF = \frac{external\ Lux\ value}{internal\ Lux\ value} = \frac{15113}{913} = 16.5531$ For x=2

$SF = \frac{external\ Lux\ value}{internal\ Lux\ value} = \frac{15113}{650} = 23.2507$ For x=3

$Elux = \frac{1}{n}\sum_{i=1}^{n} xi\ where\ xi = SF * y\ for\ each\ x\ and\ y$ (equation 8)

$$Elux = \frac{\{(11.2364 * 1334.44) + (16.5531 * 927.68) + (23.2507 * 644.9)\}}{3}$$

$Elux = 15114.89$ lux

2.4 Calculating Dimming Values with Multiple Natural Light Entries

The variable to calculate the dimming value (DimX) at each sample location changes when a room records light entering from multiple directions. To model the dimming value in this scenario, lighting software can be calibrated to reflect the internal to daylight relationship (Kacprzak and Tuleasca, 2013) which will provide the values needed to calculate SF at each lighting point. However, site sampling under each light is considered the best calibration option. This is more expensive to implement, but the accuracy that this testing provides ensures that lighting standards are met. To identify the dimming value, each lighting point needs to be known. The calculation is:

- DV = Design Value (Light Level Standard that needs to be maintained)
- Elx = External lux level
- Ilx = Internal lux level
- SF = Scale Factor
- DimX = Dimming Value that is file transferred to the lighting control system

Lux level to Scalar

$$Elx = Ilx \times SF \text{ or } Ilx = \frac{Elx}{SF} \text{ or } SF = \frac{Elx}{Ilx} \qquad \text{(equation 9)}$$

Dimming calculation (DimX) from internal lux level

$$DimX = 1 - (\frac{Ilx}{DV}) \text{ or } Ilx = (1 - Dimx) \times DV \qquad \text{(equation 10)}$$

Dimming calculation (DimX) from external lux level

$$Elx = ((1 - DimX) \times DV) \times SF \qquad \text{(equation 11)}$$

Therefore

$$Ilx = (1 - DimX) \times DV \text{ or } \frac{Elx}{SF} = (1 - DimX) \times DV \qquad \text{(equation 12)}$$

To avoid the above process of identifying DimX at a specific location, the following DimX equation is used:

$$\begin{aligned} DimX &= 1 - \left\{\frac{1}{DV} \times \left(\frac{Elx}{SF}\right)\right\} \text{ or } 1 - \left\{\frac{1}{DV} \times \left(\frac{Elx}{\frac{Elx}{Ilx}}\right)\right\} \qquad \text{(equation 13)} \\ &= 1 - \left(\frac{1}{DV} \times Ilx\right) \\ &= 1 - \frac{Ilx}{DV} \end{aligned}$$

2.5 Exponential Comparison Between Single Side Light and Multiple Light Entries

The exponential calculation in section 2.3 is used to determine internal light levels and corresponding dimming levels at a specific point when there is more than one direction of light penetrating a floor. A minimum of 3 sample plots are taken at a distance from the most dominant window as shown in figure 4. The focal point from a single direction is to be determined by the designer when light penetrates a room from 2, 3, or 4 sides. Using a North/South or East/West lux plot sample (LPS) is required. This is because the light contribution from the adjacent window is captured in the LPS. The additional factor to consider is that when the focal point is in the center of the room due to 4 directions of light. The exponential calculation must be taken from that focal point to the window, as the upward curve in both directions needs to be calculated in isolation as the rate of change could be different. This difference could be a result of window configuration, external reflectance values etc.

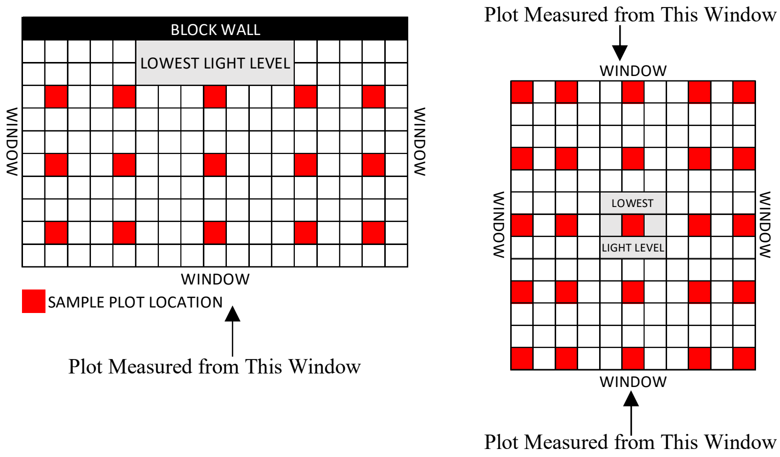


Figure 4 – Lux Plot Sample Examples

Using AGI sample plots (Table 3) in MATLAB, the exponential light distribution using the equations in section 2.3 is demonstrated graphically in figure 5 using an external lux value of 500lux. The plots in figure 6 identify the natural light level and dimming values that is needed to maintain a design of 320lux in the sample space.

Table 3 – Sample Plot (in bold) Exponential Distribution

Distance from Window in meters	Grid Spacing:			Outside Lux	15356	
	Position	GridNo1	GridNo2	GridNo3	GridNo4	GridNo5
1	PosNo1	7196	5827	5503	5830	7195
3	PosNo2	5745	3997	3572	4001	5740
5	PosNo3	5196	3273	2784	3270	5189
7	PosNo4	4915	2873	2369	2869	4912
9	PosNo5	4406	2448	2028	2443	4396

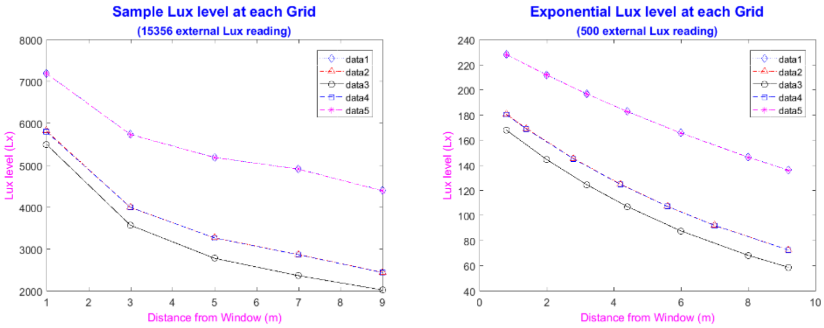


Figure 5 – Sample Plot and Exponential Lux Plot at 500 Lux

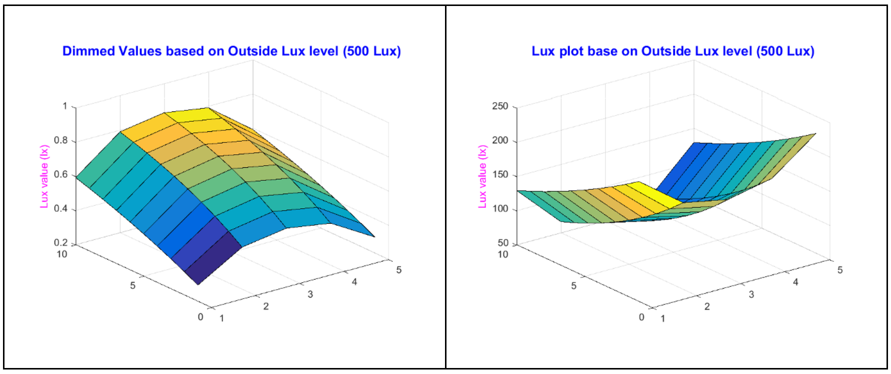


Figure 6 –Lux Plot with 3 directions of natural light

3 Future Research

The practical use of this algorithm to automating sensor-less daylight harvesting using existing lighting control technology has been implemented on a commercial project by Fredon Industries. The efficiency of SDH and financial benefits is being researched by Harris et al. (2017). To validate the worth of this research, future engineering research into; a) lifecycle benefits using AS4536 to estimate ROI, b) technical integration requirements into lighting control designs, c) removing the building weather station and use RSS feeds from the Bureau of Meteorology to determine SF, d) model lux dimming levels using matrices, e) monitor causal condition benefits that will support a business case for adopting a SDH system, f) occupant comfort levels, and g) the impact that varying artificial light has on an occupants wellbeing.

4 Conclusion

The above simulation proves that a sensor-less approach to daylight harvesting is possible. This research measures external light levels and uses an exponential equation to determine the natural lighting level at any location on a building floor. Once a floor is modelled, SF is used to identify the dimming value and 3-way relationship between internal, external, and artificial light to maintain a designed lux level. This novel approach to daylight harvesting will provide owners with increased energy savings, extend the life of a light fitting, and provide metrics to improve energy efficiencies which will benefit NABERs, Greenstar, and Well Building standards reporting.

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